VIII. Instrument Suite

A key aspects of the SAFIR mission will be the focal-plane instruments. The exquisite sensitivity made possible with the large cold telescope must be matched with cameras and spectrographs accommodating high-sensitivity, large-format far-IR / submillimeter arrays from approximately 30-1000 μm. For the purposes of credible instrumentation we generalize to this somewhat expanded wavelength regime. Here we describe our philosophy for SAFIR instrumentation, the desired measurement goals, and the strawman instrument suite that can meet SAFIR's needs.

Philosophy

The far-IR and submillimeter wavelength range is still a frontier for astrophysics, with orders of magnitude improvement possible with new technologies and new approaches. SAFIR will be a huge leap forward, optimal scientific return is made possible by following some basic principles:

1. High efficiency instruments and significantly improved infrared detectors are required in order to take full advantage of the low IR background offered by the SAFIR Observatory.

The fundamental sensitivity limit for a cold telescope in space is photon noise from the diffuse astrophysical backgrounds: thermally emitting dust in the solar-system, the Galaxy, and the aggregate of dusty galaxies at all redshifts. Detectors for SAFIR must have intrinsic noise which is comparable or below these very low photon NEPs, summarized in Appendix B. The requirements for the continuum imaging are within the achieved sensitivities of existing devices running in the laboratory, but for dispersive spectroscopy, the requirements exceed the demonstrated sensitivities of any devices. Fortunately, there are several detector approaches which are promising for meeting SAFIR's needs -- some proven in flight, others in development. These technologies and their development paths are described in detail in Section XV.A. For the purposes of developing straw-man instruments, the key point is the rapid progress made thus far. With sustained NASA funding, we can anticipate devices suitable for spectroscopy with SAFIR by the time it flies. Excellent sensitivity also requires a high-efficiency instrument: low efficiency reduces the overall sensitivity in all cases, and emphasizes the detector noise term in cases when detector noise and photon noise are comparable.

2. Astrophysical capability is increased with large-format arrays and high-throughput instruments to accommodate them.

As with the device sensitivity, detector array format is also rapidly evolving with new technologies and approaches, and SAFIR will have the potential to make a huge leap forward in array format. While FIR arrays for Spitzer and Herschel have 30--1000 elements, typically individually assembled, the technology for SAFIR will likely allow arrays with 10,000 or more elements through the use of lithographed detector and multiplexer architectures. Such array sizes are under construction for ground-based submillimeter instruments such as the SCUBA-2 camera. At long wavelengths, the AΩ product becomes large for the large arrays, and the instruments must accommodate these large throughputs. The sub-K cooling likely required for some of these large focal plane arrays imposes an additional challenge for the instrument architecture.

3. Spectral information is crucial in the far-IR, and sensitive spectroscopy is a natural niche for the single-aperture telescope.

Observations with SAFIR in the continuum will quickly be limited by source confusion, especially at the longer wavelengths. Spectroscopy provides a third dimension to distinguish multiple sources in an otherwise confused field, and thereby allows probing much deeper than in the continuum. Spectral information also provides most of the information used to guide our astrophysical understanding of the sources discovered in the continuum. Thus sensitive spectroscopic capability is crucial for SAFIR, and maximizing instantaneous spectrometer bandwidth provides the most efficient use of the observatory. The direct-detection spectroscopy takes two approaches: a low-resolution spectrometer (LRS) suite, which provides R~100 along with some imaging capability, and a moderate-resolution spectrometer (called HRS) suite which provides R~2000. R~100 provides sensitivity to spectral-energy distributions and the broad solid-state dust features, while R~2000 provides sensitive capability for spectral lines in distant galaxies. Unlike the camera architectures which are straightforward, conventional approaches for these direct-detection spectrographs may not be suitable and new approaches may be required. For the highest resolving powers necessary for detailed Galactic astrophysics experiments, a heterodyne spectrometer is needed. The heterodyne spectrometer suite is treated separately, since it is different technology from direct-detection instruments.

• Cameras and Dispersive Spectrometers

Instrument Requirements for SAFIR

SAFIR's science goals are broad, and require multiple capabilities: large field imaging across the entire wavelength band for deep surveys and maps; low resolution spectroscopy at short wavelengths to probe broad continuum and solid state features in debris disks; and medium resolution sensitive spectroscopy for measuring extragalactic emission lines from cosmologically distant sources.

The measurement goals for SAFIR's direct-detection instruments are generated assuming optimistic detector array development and are presented in Table VIII-1. Spectral regions are split up typically by octaves, and a detector technology along with the focal-plane assembly, pixel size, and operating temperature is listed for each range. An important constraint is the size of the instruments: the entire suite is must fit in to SAFIR's fiducial instrument chamber – an assumed 4 m diameter by 3 m tall enclosure located directly behind the Optical Telescope Assembly (OTA).

Instrument	Wave-length range (um)	Spectral resolving power (R)	Field of View (FOV) (arcsec)	IFOV (arcsec)		Detector physical size (um)	FPA format NxN	FPA type	FPA temp (K)	Comments
CAM	20 - 600									Simultaneous image in two fields of different size
CAM1	20 - 100	R~5	60x60	0.47		500	128x128	Ge:Ga?	<2?	Plus six postion filter wheel
CAM2	140 - 600	R~5	240x240	1.88		1000	128x128			Plus six postion filter wheel
LRS	20 - 100									Two simultaneous integral
LRS1a	25 to 40	100	6 x 6	0.4		40	< 512 by 512	Si:Sb	4?	field (image slicer)
LRS1b	35 to 70	100	9 x 9	0.7		1000	128 x 128	bolometers	0.1	spectrographs
LRS1c	60 to 100	100	12 x 12	1		500	128x128	Ge:Ga	1.8?	
HRS	20 - 720									
HRS1a	20 to 40	2000	18 x 18	0.4		40	< 512 by 512	Si:Sb		
HRS1b	35 to 70	2000	18 x 18	0.7		1000	8 by TBD	bolometers	0.1	
HRS1c	60 to 120	2000	18 x 18	1.2		500	8 by TBD	Ge:Ga	2?	
HRS2a	120 to 240	2000	18x96	2.4		1000	8 by TBD	bolometers	0.1	
HRS2b	200 to 400	2000	18x96	4		1000	8 by TBD	bolometers	0.1	
HRS2c	360 to 720	2000	18x96	7.2		1000	8 by TBD	bolometers	0.1	

Table VIII-1: SAFIR instrument suite goals – direct detection.

Approach to strawman instrument designs

Most of the direct-detection instrument for SAFIR will be conventional reflective optics designs, and SAFIR's Vision Mission study has relied on Ball Aerospace for generating innovative optical designs for these instruments, at their own cost. These conventional cameras and spectrographs form the bulk of the instrument complement for SAFIR, and Ball is an excellent partner for this effort, given their successful delivery of instruments for Spitzer and Hubble. In addition to the conventional approaches, members of the science team are also developing new instrument architectures which complement the conventional approaches, such as the waveguide far-IR grating spectrometer (WaFIRS), and the heterodyne spectrometers.

At this early stage, it is difficult to speculate about the breakdown of instrument use on SAFIR. Spitzer provides some idea of the requests that SAFIR might experience. Based on recent accepted proposals, Spitzer science topics are fairly uniformly distributed among cosmological, local universe, star and planet formation, ISM, and Solar System investigations. Imaging comprises about 63% of the telescope time, divided evenly between IRAC and MIPS. The mean integration time requested is close to 1000 sec. If SAFIR is used similarly, the cameras will be the most utilized instruments. This is not unreasonable; at a wavelength of 70 µm, broadband observations with SAFIR will take around 400,000 sec to be thoroughly confusion-limited. At longer wavelengths this time is much shorter. This is shown below in Figure VIII-1, which illustrates that the usable integration time varies significantly across the SAFIR band.

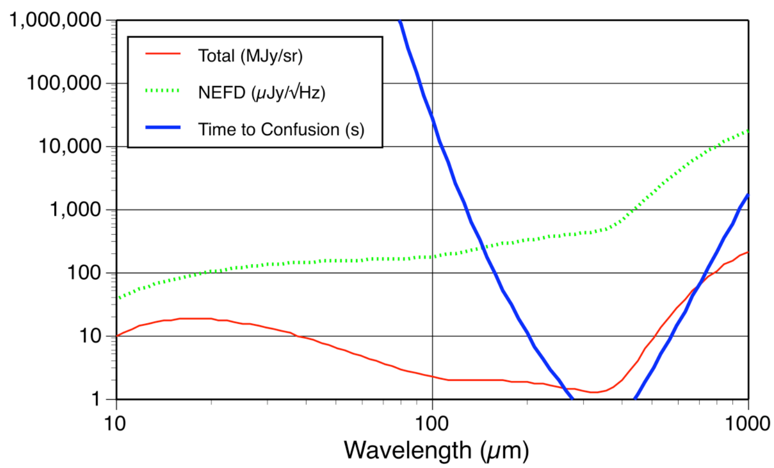


Figure VIII-1: Sky brightness, broadband noise equivalent flux density (NEFD), and the time required to integrate down to the confusion limit as a function of wavelength.

There are several features of an ideal camera for SAFIR. For the required field of view, the detector array should capture both polarizations of all spatial modes illuminating the focal plane. There should be a clean (or at least stable) point spread function, with low stray light or spurious illumination. At short wavelengths, the dynamic range must be high and integration times will be long. The number of pixels must be large, and the quantum efficiency must be high. At longer wavelengths, the integration times will be short and so changing filters or sweeping around the sky must be quick. Smaller arrays with an agile steering mirror may be a more effective implementation of a long wavelength camera.

Ball Aerospace approach to conventional cameras and spectrographs

Ball's role in this study has been to develop generic far infrared imager and spectrometer concepts based on proven approaches, then to estimate dimensions, volume, and mass for the instrument complex. A generic functional block diagram for either a camera or a spectrometer, shown in Figure VIII-2. The hardware to support those functions is divided into the cold optical portion of the instrument, the warmer (often ambient temperature) instrument electronics, the software to interface to the spacecraft and control the instrument, and the ambient and cryogenic cables within the instrument and between the instrument and the spacecraft. Optical designs are the first step, and the approach has been use all-reflective, all-aluminum optics where possible, as this approaches is cryogenically friendly, mechanically robust, and has a large degree of flight heritage.

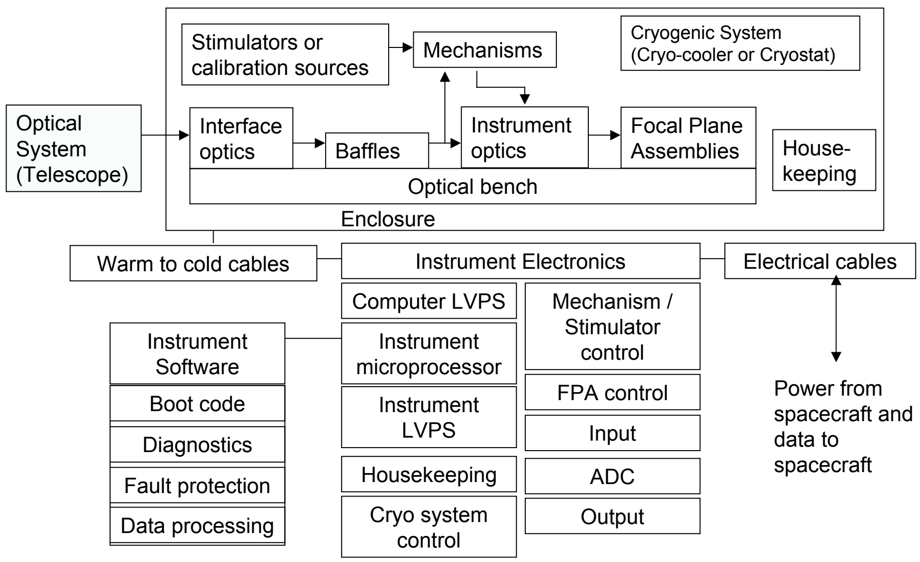


Figure VIII-2: Generalized IR Imaging or Spectrometer Instrument Functional Block Diagram

Camera Designs

The initial conceptual design for the cameras is straightforward, based on the NICMOS imaging channels (confocal parabolas and a field mirror to relay the pupil) and the concepts for both sub-modules – Cam1 and Cam2 – are similar (See Figure VIII-3). As a result of what we consider to be relative optical simplicity, we present only a top level concept. The camera concept consists of a field separator at the telescope focal plane, a dichroic separating the Cam1 and Cam2 spectral regions, a field mirror, a collimator, a camera mirror, and fold mirror, and the arrays. The backends of Cam1 and Cam2 are similar in concept but slightly different in detail.

The real exit pupil in image space enables 100% cold stop efficient system baffling. The camera relay optics are in the OTA temperature space. The exit pupil, cold filters, and detector array are in the staged cooler (shields) temperature space. The field mirror radius of curvature is used to locate the exit pupil at the desired location.

The largest optical element in either camera is less than 40 cm in diameter. The Cam1 module packaging dimensions are ~4 x 0.4 x 0.6 m for an associated volume of less than 1.0 m^3. The Cam2 module is about half the length of the Cam1 module with similar width and height. Its volume is of the order of 0.5 m^3. Although much of the volume is empty, assuming a typical cryogenic instrument density of 0.2 g/cc, the Cam1 instrument mass is about 200 kg and Cam2 is of the order of 100 kg.

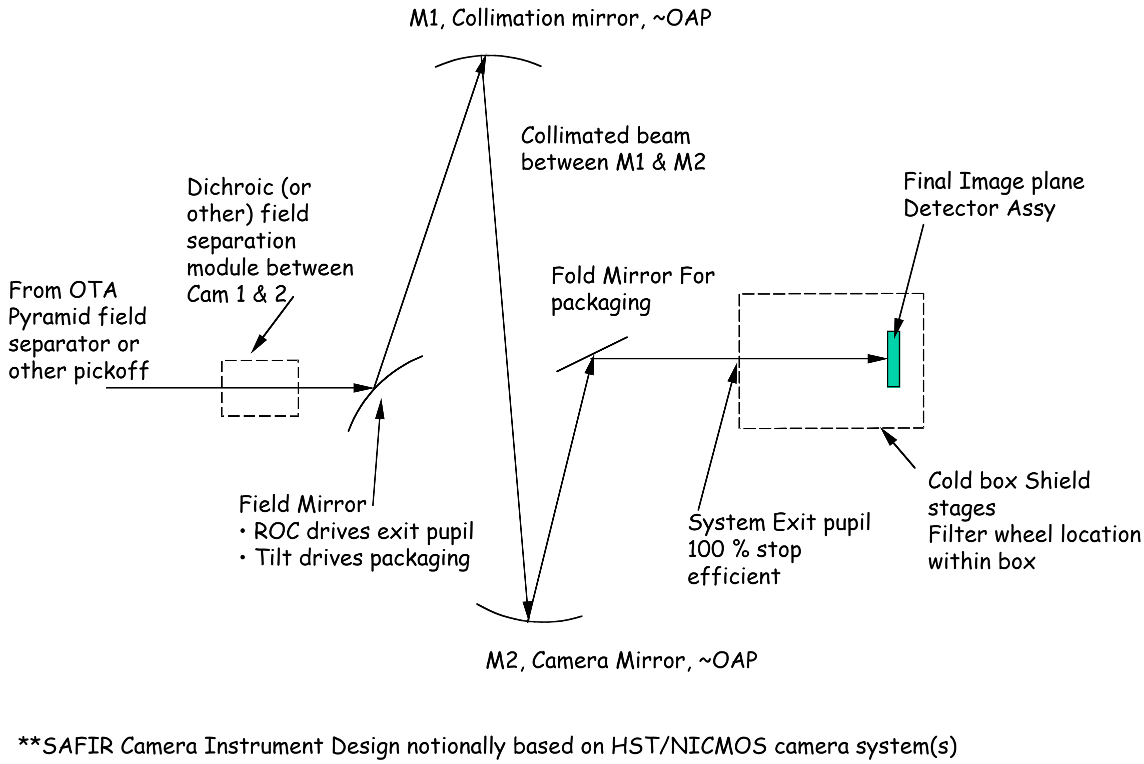


Figure VIII-3: Camera concept for SAFIR Cam1 and Cam2

While not prohibitive, these masses are large and future trade studies should investigate methods to reduce the size and the mass of the camera modules. Alternate relay approaches to the original confocal parabolas for the collimator and camera, such as an Offner-like aspheric relay or an off-axis Cassegrain collimator and camera could potentially reduce the size. Also a faster camera could also be smaller, but this requires a small detector plate scale.

Low-resolution spectrometer designs
SAFIR's LRS is based on a ruled reflection grating and has three sub-bands (LRS1a, LRS1b, and LRS1c) covering the 20-100 µm regime at a resolving power of 100. The three modules are first order, long slit spectrometers with pre-slit integral field slicing units – as shown in the block diagram in Figure VIII-4**.** The first optical element is included to relay the image (for packaging purposes) onto the dichroic beam splitter assembly, which separates the incoming light into three sub-bands.

The three fields of view (FOVs) of the three sub-bands are co-boresighted to provide instantaneous broadband coverage on the sky. After spectral separation, an image slicer assembly re-packs the area FOV into line pseudo-slits for subsequent spectrometer dispersion. At this location, magnification can be changed if required.

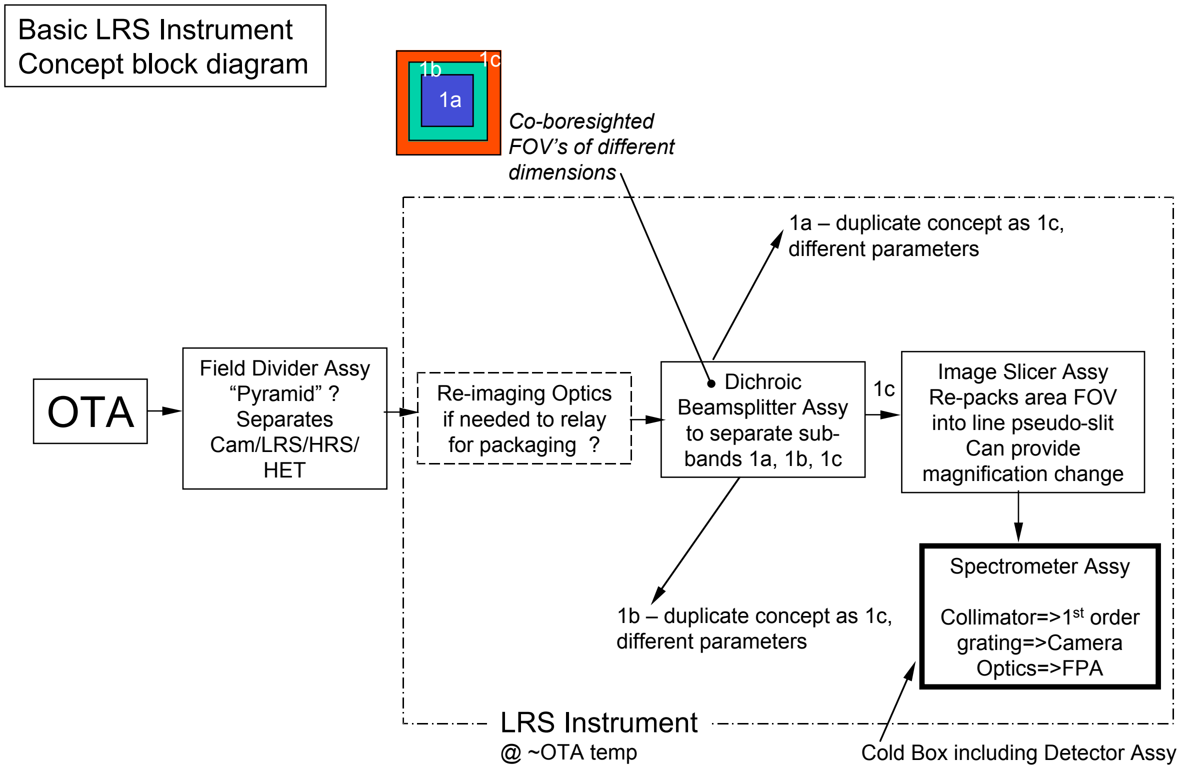


Figure VIII-4: Low Resolution Spectrometer with three sub-bands covering 30 to 100 μm at R=100.

Figure VIII-5 below shows the optical design of a low-resolution spectrometer image slicer assembly for one band (LRS1a). The slicer can accommodate variable magnification between the entrance area field and re-imaged pseudo slit. This implementation is limited by the number of slices in the slicing mirror assembly. The detector array format and the number of slices are related, and are a topic for future investigation as the array technology matures.

The optical design assumes a slit width of λ/D where D is the telescope diameter and λ is the maximum wavelength in each sub-band, and that the slit is sampled with two pixels. The three spectrometer modules are optimized for each sub-band but are similar in concept. The light then enters the spectrometer assembly – a collimator, a first order ruled low-blaze-angle reflection grating, a wide field of view camera mirror, and the focal plane array. Figure VIII-6 shows the first order spectrometer layout for one of the sub-bands—the other sub-bands scale. Several options also exist for the implementation of the final re-imaging camera. A reflective Schmidt camera is one option but the packaging volume is generally greater and it produces substantial field curvature. For spectral resolving power of 100, about 200 pixels are required in the spectral direction for each sub-band. For Band LRS1a the spatial / imaging dimension is 3.65 mm or about 92 pixels, which fits comfortably on the arrays being developed for SAFIR.

The largest optical element in the LRS is less than 12 cm; the volume is less than 0.02 m^3. Taking the density of 0.2 g/cc, the mass of each module is around 4 kg. As a point of reference, the modules of the Spitzer Infrared Spectrometer (IRS) had envelope dimensions of approximately 20 x 20 x 30 cm

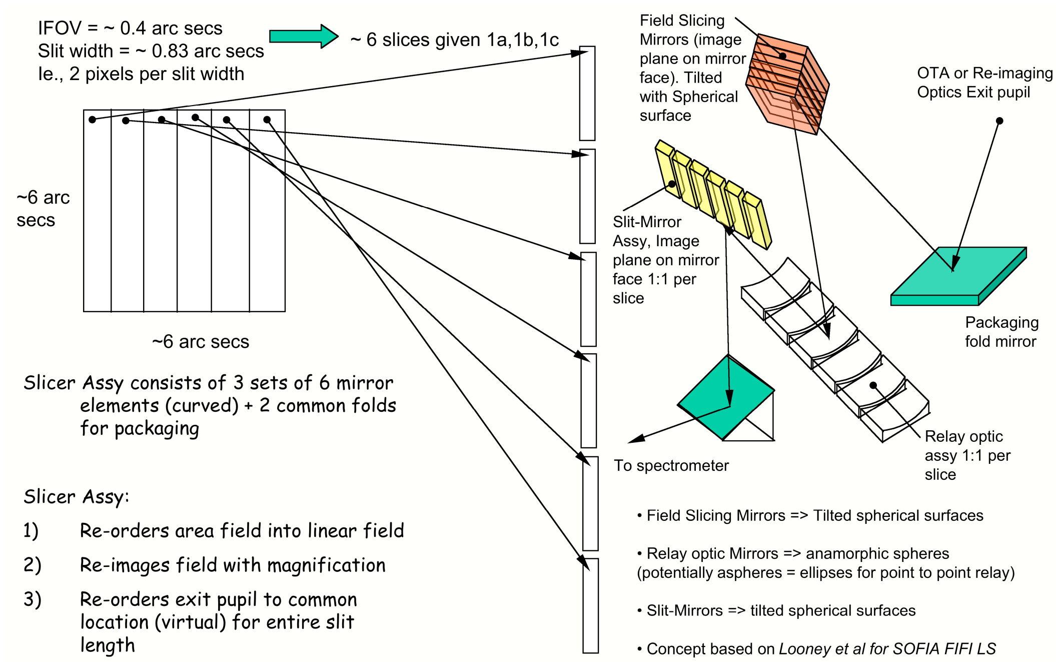


Figure VIII-5: SAFIR Low Resolution Spectrometer Individual Band (LRS1a) Image Slicer Assembly

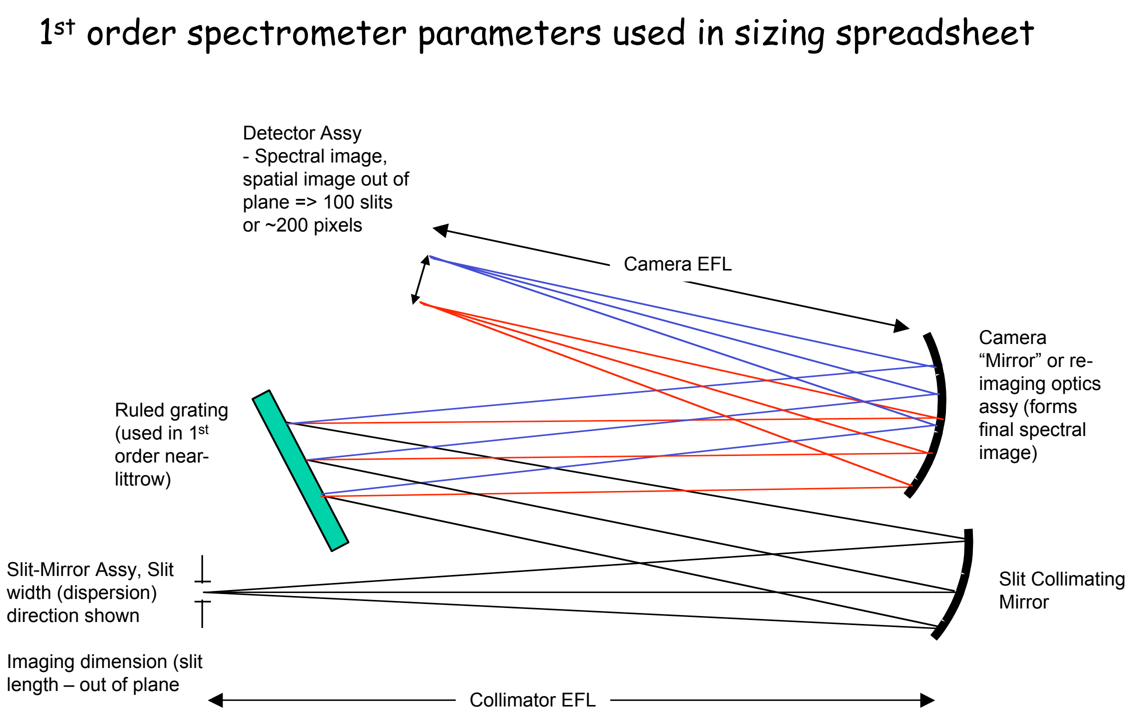


Figure VIII-6: Low Resolution Spectrometer Spectrometer Assembly.

for a typical envelope volume of approximately 0.012 m^3. The mass of each module was of the order of 3 to 4 kg. A small optical envelope and a small volume may not allow room for detector arrays, baffles, etc. Even though the LRS1a module is quite small, there are overheads, and the study adopts a typical size of 20 x 30 x 30 cm and a mass of about 4 kg per LRS module for volume and mass budgets.

The properties of the conceptual camera and low resolution spectrometer are listed in Table VIII-2.

SAFIR CAMERAS AND LOW-RESOLUTION SPECTROMETERS									
					Envelope Dimensions				
Module	Range (micron)	Resolving power	FOV (arcsec)	Beam (arcsec)	Length (cm)	Width (cm)	Height (cm)	Volume (m^3)	Mass (Kg)
CAM	20 - 600								
CAM1	20 - 100	R~5	60x60	0.47	400	40	60	1.0	192
CAM2	140 - 600	R~5	240x240	1.88	200	40	60	0.5	96
LRS	20 - 100								
LRS1a	25 to 40	100	6 x 6	0.4	12	11	7.0	0.001	0.2
LRS1b	35 to 70	100	9 x 9	0.7	26	42	16	0.02	3.5
LRS1c	60 to 100	100	12 x 12	1	31	32	18	0.02	3.6
Note: To convert instrument / module volume to mass, a density of 0.2 g/cc is assumed.									

Table VIII-2: SAFIR camera and low-resolution dispersive spectrometer module summary

Moderate Resolution Spectrometer

The moderate-resolution spectrometer (HRS) modules employ ruled Echelle reflection gratings. Initial concepts for the shorter bands (1a, 1b, and 1c) were long slit spectrometers using an integral field spectrograph approach with a pre-slit slicing mirror assembly. There is a coarse Echelle for the main dispersion and grating cross-disperser for order separation, followed by a wide field of view camera re-imaging optics assembly focusing the light onto the detectors. At present, the optical models assume a first order perfect lens for the camera. As the design matures, this will be replaced with a true wide-field all-reflective camera system, likely a three-mirror antistigmat (TMA) or Schmidt camera.

Unfortunately, the HRS modules that work well at the short wavelengths cannot be used at the longest wavelengths for SAFIR. Using the same approach for all wavelengths requires that all linear dimensions scale as λ, thus the volume scales as a factor close to λ^3 (assuming a constant input focal ratio and spectral resolution). For HRS1a, typical dimensions are 80 x 50 x 40 cm, and scaling this to HRS2c results in a module many meters in size. It is clear that generating a compact moderate-resolution spectrometer design is critical for SAFIR, and this has been the subject of a detailed trade study for the cross-dispersed echelle design. The team focused on producing a 360-720 μm echelle spectrometer which only couples a single point source on the sky, but which is as compact as possible. Four parameters were considered in this trade study: Echelle blaze angle, input focal ratio to the spectrometer slit, spectral resolution, and pixel dimension. Figure VIII-7 plots the parametric study results in graphical form.

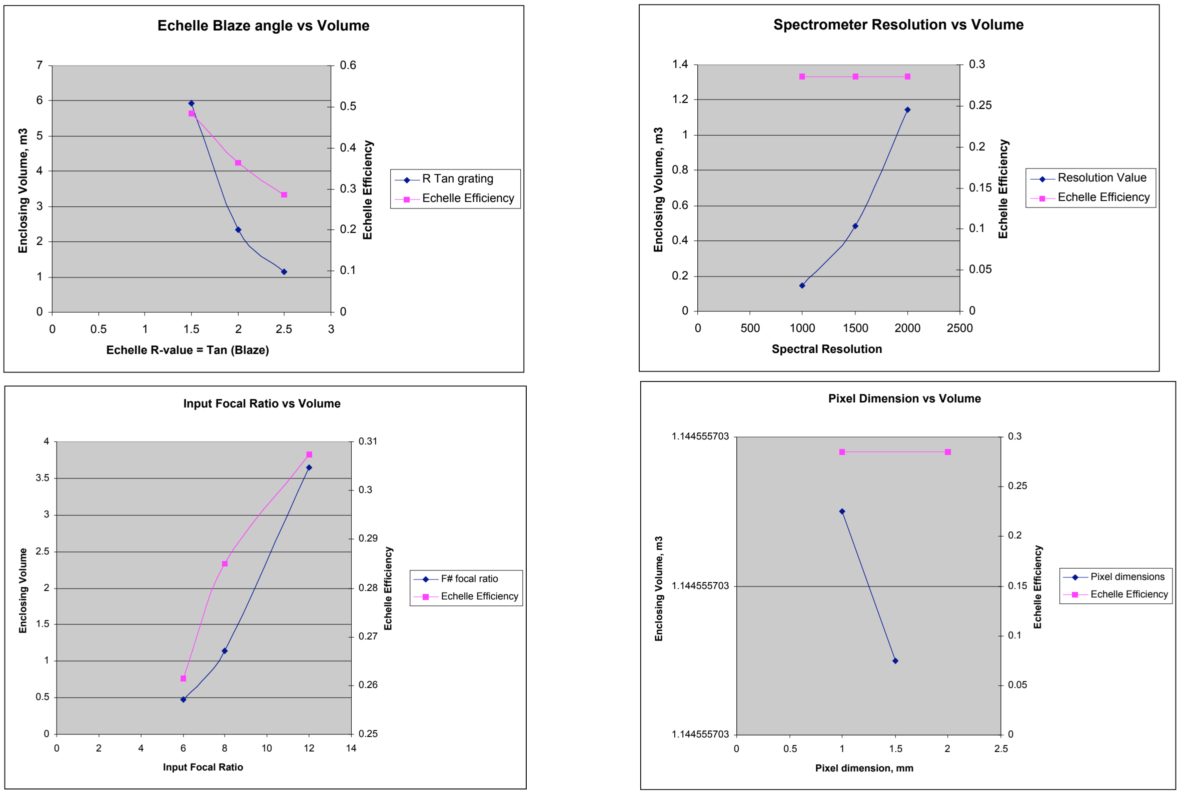


Figure VIII-7: Graphical Summary of Results of Parametric Evaluation

In summary:

1. Increasing echelle blaze angle (R-value) has significant effect of volume reduction, but comes with significant penalty on system efficiency. This can be understood in terms of groove shadowing on the echelle. High R-values also impact anamorphic magnification, which is inefficient for square pixels, and recommends rectangular pixels.
2. Reducing input focal ratio (prior to slit) offers a significant volume reduction, with only modest impact on system efficiency. Speeding up the system also introduces greater anamorphic magnification.
3. Reducing the spectral resolving power of the module offers a significant volume reduction, with no impact on normalized system efficiency.
4. Pixel dimension (plate scale) has no impact on the volume so long as the camera focal ratio is not too large (>3).

The parametric study indicates that the instrument volume scales $(R*\lambda*F/\#)^3$, and that it also can be reduced by steepening the echelle angle. Given these results, a compact design was adopted with a fast camera with pixel size of 1.4 λ_{max}. Figure VIII-8 and VIII-9 show the layout and dimensions for the largest and most massive module, the 360 to 720 μm HRS2C. Figure VIII-10 shows the Echellogram, and Figure VIII-11 the efficiency for HRS2C. This module is substantially smaller than any previous design for an echelle device, and at 3 m in the longest dimensions, is approaching the realm of possibility for SAFIR. Using this longest module as the baseline, the shorter wavelength modules can be scaled by their wavelength ratios and the results are presented in Table VIII-3. Clearly, at the shorter wavelengths, the modules are very small, and the requirement on compactness can be relaxed to recover some imaging capability and increased efficiency.

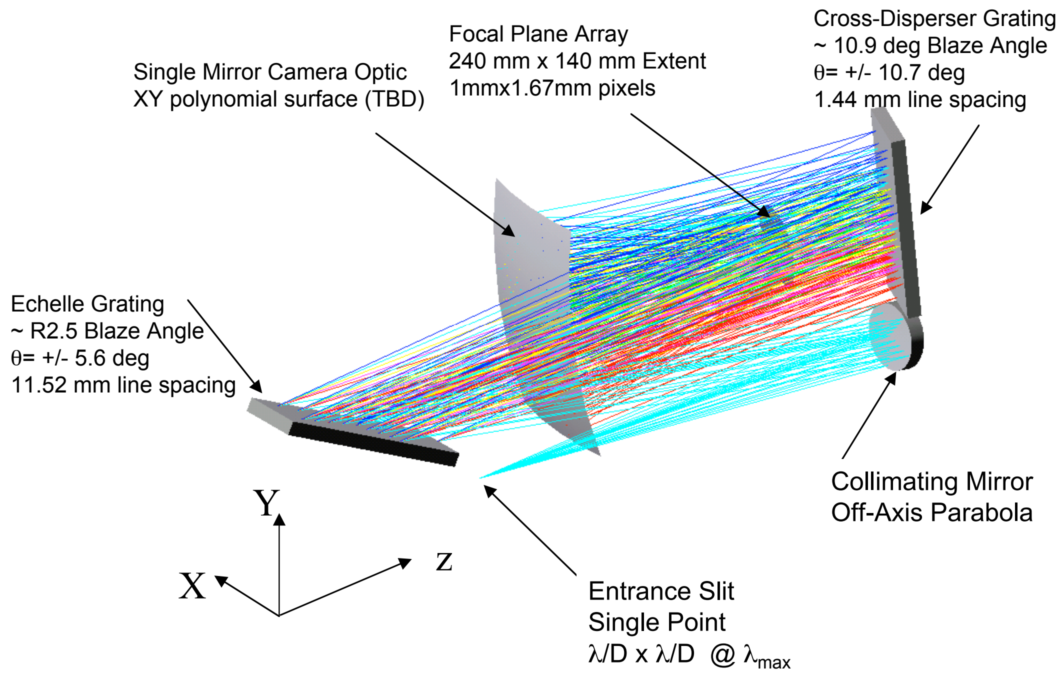


Figure VIII-8: SAFIR HRS2C band cross-dispersed Echelle spectrometer concept illustrated.

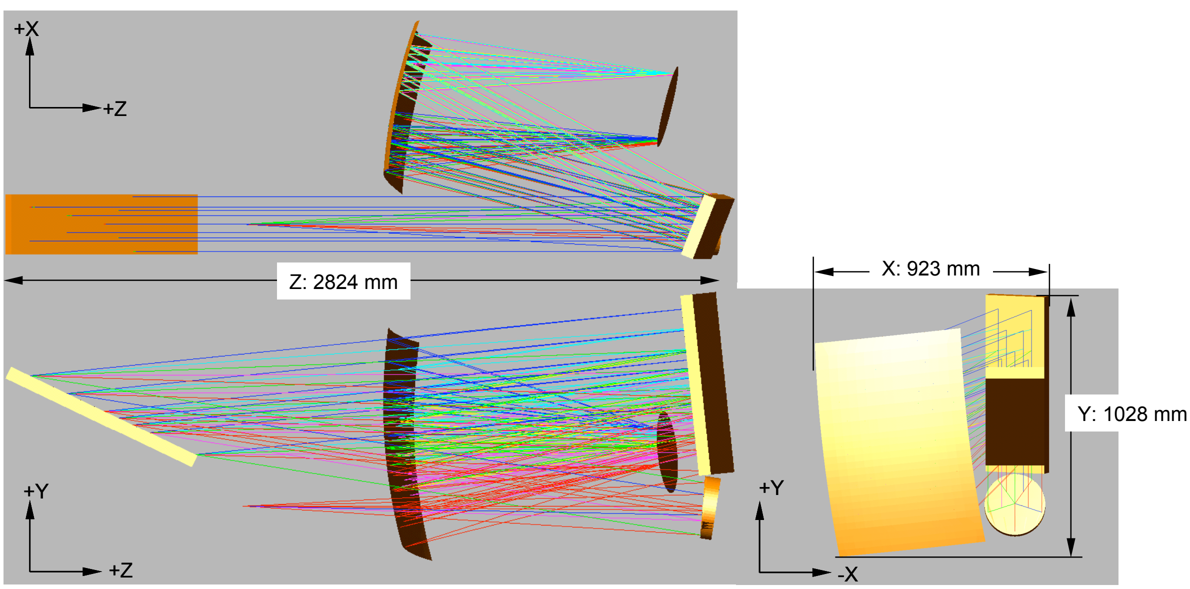
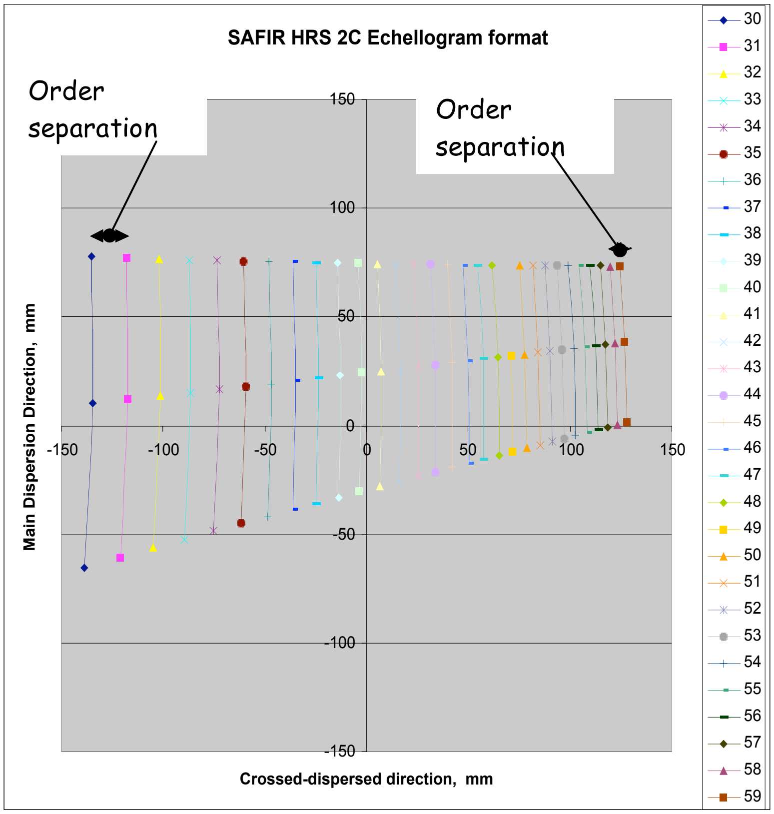


Figure VIII-9: SAFIR HRS Band 2C layout.



- Spectral range covered
  - 360 to 720 μm
- Orders used
  - m =30 to 59
- Echelle Blaze angle
  - R2.5, 68 deg
- Overall FPA format
  - 260 mm in X-disp direction
  - 143 mm Main-Disp. Direction @ M=30
  - Direction @ M=59
- Pixel Dimension
  - 1000 μm in Main-Disp. direction
  - 1640 μm in X-disp direction
  - difference due to anamorphic pupil with R2.5 echelle

Figure VIII-10: SAFIR HRS2C channel Echellogram (FPA arrangement) for a single field point slit (minimum slit spectral and spatial at maximum wavelength).

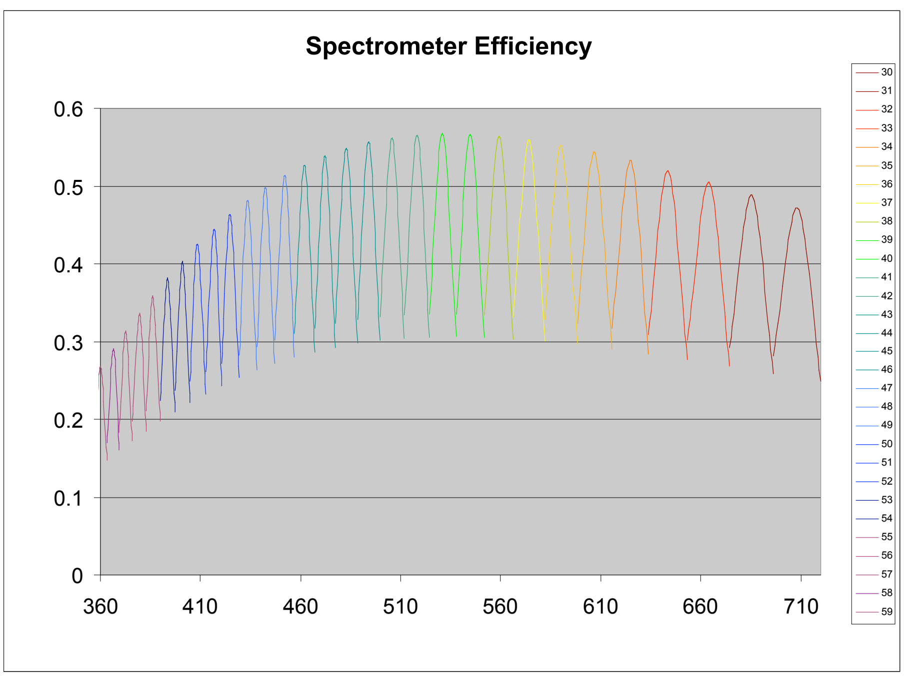


Figure VIII-11: Efficiency of SAFIR HRS Band 2C.

SAFIR HRS module summary												
		Spec	FOV		array	Pixel size		Dimensions				
		res.		Beam	format	(Spec)	(Spat)	L	W	H	Vol	M
Module	Range	power	(“)	(arcsec)		(um)	(um)	(cm)	(cm)	(cm)	(m^3)	(Kg)
HRS1a	20-40	2000	0.83	0.42	150 x 160	56	91	16	5	6	5^-4	0.10
HRS1b	35-70	2000	1.44	0.72	150 x 160	97	160	28	9	10	0.003	0.50
HRS1c	60-120	2000	2.48	1.24	150 x 160	170	270	50	16	17	0.014	2.7
HRS2a	120-240	2000	5	2.5	150 x 160	330	550	94	31	35	0.10	20
HRS2b	200-400	2000	8.3	4.1	150 x 160	560	910	160	52	57	0.47	95
HRS2c	360-720	2000	15	7.5	150 x 160	1000	1640	280	95	100	2.66	532
Note: To convert module volume to mass, cryogenic instrument mass density of 0.2 g/cc assumed												

Table VIII-3: SAFIR moderate-resolution module summary.

In brief, the cameras, low-resolution spectrometer, and short-wavelength moderate resolution spectrometers are all feasible and can achieve the desired goals. For the longest-wavelength HRS modules, a compact, single-spatial-beam spectrometer is possible.

Waveguide Far-IR Spectrometer (WaFIRS) Approach

As the parametric study conducted by Ball has demonstrated, the size of conventional cross-dispersed echelle spectrographs remains large even after optimization. A single module for the long wavelengths measures over 3 m in the longest dimension! Given that the full instrument complement will include several instruments in an instrument volume which is of order 3 m, this is arguably too large for a single module of one instrument. Even if a single module could be included, the approach offers little flexibility for multiple modules to provide spatial multiplexing.

As an alternative, members of the SAFIR team are demonstrating a new technology which is more compact. The Waveguide Far-IR Spectrometer (WaFIRS) uses a single curved grating in a parallel-plate waveguide to provide a broadband spectrum of a point source, as shown in Figure VIII-12. The concept benefits from the fact that at long wavelengths, the grating surface can be machined which allows for good optical performance at fast F#, and without the need for the collimating and reimaging optics that a ruled grating requires. By limiting the spatial extent to a single point source, propagation in the spectrometer can be put into waveguide, and the system becomes entirely two-dimensional. SAFIR science team members are prototyping a WaFIRS system for ground-based observations in the 1-1.6 mm band. Extensibility to shorter wavelengths appears straightforward.

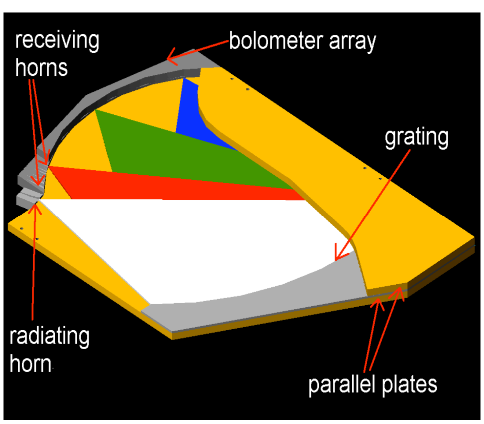


Figure VII-12. Waveguide far-IR spectrometer (WaFIRS) concept. Light propagates in a 2-D parallel-plate waveguide, and is diffracted and focused by a custom machined grating surface on one side. Detectors are arrayed on the other side, and span a bandwidth of 1:1.6 or greater.

A WaFIRS module size scales as the product of resolving power and wavelength – but since the device is two-dimensional, the volume only scales as the square of this product, instead of the cube as in a conventional free-space spectrograph. Scaling to a R~2000 device for 400-700 µm results in a size just over 1 m square, with further reduction possible with modest penalties in efficiency. Finally, the 2-D waveguide architecture offers the potential for dielectric immersion, which would further reduce all dimensions by the index (3.4 for silicon). Table VIII-4 below shows how the properties of a SAFIR WaFIRS-like spectrometer would compare with the Z-Spec version already in operation.

Design Parameter		Z-Spec (built)	SAFIR far-IR	SAFIR far-IR
Wavelength	µm	970-1630	160-300	160-300
Medium		Vacuum	Vacuum	Silicon
Detectors	#	160	500	500
Facets	#	480	4000	4000
Resolving Power	$\lambda/\Delta\lambda$	250-400	1000-1600	1000-1600
Spacing	mm	2.5	0.6	0.18
Tolerance	µm	40	5	1.5
Length	mm	610	550	160
Efficiency		0.78-0.85	0.90-0.93	0.90-0.93

Table VIII-4: Properties of the currently operating Z-Spec WaFIRS architecture spectrometer is compared with possible SAFIR concepts.

A WaFIRS design is thus an excellent candidate for SAFIR because of its versatility. Multiple modules can be readily stacked in the SAFIR instrument envelope to multiplex in position of frequency or both. Each spectrometer is single-polarization, and two polarizations from the sky are separated with a grid, then each polarization is be used for three spectrometer modules. By staggering the wavelength bands, such that polarization A couples bands 1, 3 and 5 while B couples 2, 4 and 6, the dichroics which separate the bands do not require a sharp transition. The combination of a polarizer and 4 dichroics thereby provides complete instantaneous coverage over the full band for a point source.

• Heterodyne Spectrometers

The use of heterodyne spectrometers on SAFIR is justified somewhat differently. All heterodyne systems suffer quantum noise--in the THz regime, this is orders of magnitude greater than the photons noise from the astrophysical backgrounds, so a cold SAFIR is not required for optimal heterodyne use. Nevertheless, heterodyne spectroscopy is the only way to get very high velocity resolution (~ 1 km/s) required for unique galactic astrophysics experiments such as probing dynamics of cloud collapse and star formation. While heterodyne spectroscopy does not drive the thermal management of SAFIR, it is highly enabled by the size of the collecting area. Table VIII-4 outlines a potential suite of heterodyne instruments for SAFIR.

Instrument	Wave-length range (um)	Spectral resolving power	Field of View (FOV) (arcsec)	IFOV (arcsec)	Detector physical size (um)	FPA format NxN	FPA type	FPA temp (K)	Comments
HET	25 - 520								Five Fields with field sharing
HET1	20 to 40	100,000	4	1.65	f/1.5 beam onto the detector	2 x 2 array nearly close packed	Hot electron bolometers (HEBs)	0.1	Sparsely sampled array of single moded detectors with each pixel being one diffraction limited beamwidth (2 lambda / D)
HET2	40 to 80	100,000	8	3.3	f/1.5 incoming beam onto the detector	2 x 2 array of bolometers nearly close packed	Hot electron bolometers (HEBs)	0.1	Sparsely sampled array of single moded detectors with each pixel being one diffraction limited beamwidth (2 lambda / D)
HET3	80 to 160	100,000	16	6.6	f/1.5 incoming beam onto the detector	2 x 2 array of bolometers nearly close packed	Hot electron bolometers (HEBs)	0.1	Sparsely sampled array of single moded detectors with each pixel being one diffraction limited beamwidth (2 lambda / D)
HET4	160 to 320	100,000	32	13	f/1.5 incoming beam onto the detector	2 x 2 array of bolometers nearly close packed	Hot electron bolometers (HEBs)	0.1	Sparsely sampled array of single moded detectors with each pixel being one diffraction limited beamwidth (2 lambda / D)
HET5	300 to 520	100,000	64	22	Make an f/1.5 incoming beam onto the detector	2 x 2 array of bolometers nearly close packed	Hot electron bolometers (HEBs)	0.1	Sparsely sampled array of single moded detectors with each pixel being one diffraction limited beamwidth (2 lambda / D)

Table VIII-4: SAFIR Heterodyne spectrometer modules

The figure of merit for a heterodyne system is the receiver temperature, usually given in units of Kelvin. All heterodyne systems are ultimately limited by quantum noise in the down conversion process which is hν/k or about 50 K/THz. The current state of the art can be divided up into four frequency ranges:

1. Amplifiers (below ~150 GHz)--state of the art is about 5 hν/k.

2. SIS mixers to Nb band gap (below ~750 GHz)--state of the art is 2-4 hν/k.

3. SIS mixers between 750 and 1300 GHz--state of the art is 4-8 hν/k.

4. HEB mixers above 600 GHz (tested to 5.2 THz) state of the art is 10-20 hν/k

The achievable IF bandwidth is an important consideration, particularly at the highest frequencies, for which the fractional band of a fixed IF bandwidth is reduced. Bandwidths to 12 GHz in SIS receivers have been demonstrated and development to 20 GHz is underway. HEB mixers have limited implementation history and have IF bandwidths limited by the phonon cooling time of the device. For the best phonon cooled devices this means that the IF is currently limited to about 5 GHz.

A local oscillator (LO) is required for all mixer receivers. A frequency-agile LO is important and difficult -- while mixers might have 100-500 GHz of bandwidth, the local oscillators are almost always more limited in bandwidth. LOs can be constructed from a variety of technologies:

1. Harmonic Generation. The state of the art is varactor diode based multipliers with high conversion efficiency. Effectively these are limited by the Q of the resonant circuit to bandwidths of 10-15%. Resistive versions can be designed allowing for wider bandwidths 10-30% at the cost of conversion efficiency. Power levels are sufficient to pump modest arrays to about 1 THz and a couple pixels to 2 THz. There are good prospects to extend the technology to 3 THz in the near future.

2. Gas Lasers. Gas lasers have high output power and can pump large arrays of devices but they have no ability to tune so system bandwidth is limited to that which can be achieved in the mixer IF.

3. Diode Lasers. In the short wavelength limit of SAFIR quantum cascade lasers have been used to pump mid infrared mixers (10-20 μm). Initial experiments with recently developed far infrared Quantum Cascade lasers have been encouraging but are far from a serviceable LO. Bandwidths are currently only a few percent.

4. Photomixing. There are a few demonstrations of beating two near optical lasers together to generate a difference frequency as the local oscillator. The advantage of this approach is potentially a very wide bandwidth (several octaves), but it has been plagued by poor optical-to-far IR conversion efficiency.

Harmonic LOs have been demonstrated for Herschel for frequencies below 2 THz, but some simplification is required and the LO is still an unsolved problem for frequencies beyond 2 THz.

The Intermediate Frequency (IF) system is typically based on HEMT amplifiers operating at about 20 K. The current generation of InP based HEMT amplifiers achieves 3-5 times the quantum limit in noise performance and dissipates about 1mW per gain stage (~12 dB) where about 40 dB is necessary to extract the signal from the cryostat. Amplifiers with up to 20 GHz of bandwidth have been built. There are prospects for lower-power operation in the system context--the major challenge will be engineering the thermal break between cold mixer and warmer IF amplifier without loading the mixer or introducing excessive losses.

The backend spectrometers are also currently a limitation for heterodyne systems. There are several types of spectrometers in use. These include digital correlators, analog correlators, acousto-optical spectrometers, filter banks and chirp transform spectrometers. The figures of merit are bandwidth, resolution and power per resolution element. It is also critical to note that some spectrometers have adjustable resolution while others are fixed resolution.

1. Digital correlation spectrometers employ a sampler and a digital delay to autocorrelate the spectra. The power consumption is generally proportional to the speed of the electronics. The state of the art bandwidth is about 1 GHz and the power consumption is a few mW per lag.

2. Analog correlators use analog mixers and predefined time delays (length) to correlate signals. They are well suited for looking at wide bandwidths with fewer resolution elements than their digital devices. On the ground power consumption is not an issue so these units typically run hundreds of mW per channel, but that could be significantly reduced. The channel width cannot be easily re-adjusted.

3. Acousto-optical spectrometers have been used on a number of space missions and have wide bandwidth 1-1.5 GHz per acoustic element. They also generally have very low power and have been implemented with up to 4 elements stitched together. Power is typically 5-10W per

GHz of spectra analyzed. There are good prospects for wider bandwidth spectrometers, but the channel width cannot be re-adjusted.

4. Filter banks have the least flexibility and are better suited for atmospheric applications where the shape of the observed feature is known in advance so the filter bank can be engineered. The power is almost always dominated by the IF processing required.

5. Chirp transform spectrometers are time domain spectrometers using digital electronics. As such they can be made low power with a few mW per resolution element and can be tuned in resolution with careful adjustment of the chirp.

The SAFIR instrument will place stringent demands on the number of pixels in the spectrometer and on its power consumption. Moore's law suggests that the digital systems will soon offer enormous advantages in capability over their analog counterparts; however significant development is still required.

Development Needs

Mixers

There are a number of developments required to assure that there is either a mixer or available to cover the SAFIR bands. SIS technology is well established especially below the Nb band gap at 750 GHz. As a result, the focus needs to be on the development of more complicated circuits (balance mixers, side band separation mixers) and reduction in complexity and increase in functional integration. These include more integrated devices including IF circuitry, possibly LO, elimination of magnets and the ability to mass produce the mixer with a minimum of human intervention.

In the region between 750 GHz and about 2.5 THz, there is much progress to be made with SIS mixers. The unknown losses in Herschel mixers above 1 THz need to be understood and addressed. This would reduce the noise level to that comparable to the mixers below the Nb band gap. Secondly a development program using NbTiN/I/NbTiN or NbN/I/NbN junctions (I=insulator) extending the useful range to >2THz should be undertaken. Lastly these need to be implemented into more complex circuits based on the experience gained below 750 GHz.

For HEB mixers it remains unknown what the fundamental limitations of the sensitivity really are. They are quantum limited, but it remains unclear and uncertain what the effects of losses to the thermal heat sink really are. These may limit the sensitivity or require some sophisticated device engineering to get around. The limited bandwidth is clearly a potential problem for SAFIR which must be addressed. Lastly the issues associated with making more complicated circuits need to be tackled along with simplified implementation of mixers.

Due to the seriously limiting problem of bandwidth in HEB mixers, efforts to find and identify a wider IF band mixer technology must be a priority above the current SIS limit. Unfortunately all the known potential alternatives are at very low technology readiness levels where questions about the fundamental physics still being addressed.

Local Oscillators

The progress in harmonic generators has been spectacular due to improvements in E&M solvers and the advent of precision lithography made planar diodes. The lessons learned in the Herschel development suggest that the technology is extendable to about 3 THz. Further extensions will require improvements in device power handling or the application of drive power at progressively higher frequencies. Specific steps for development include demonstration of 2-3 THz multipliers, improvements power handling in the 100-500 GHz range, development of power amplifiers to frequencies higher than 110 GHz, increased functional integration of circuits (e.g. multipliers combining multiple stages in a single block and ultimately a single device to reduce losses) and simplified fabrication and assembly.

The big hope for local oscillators is the quantum cascade laser which offers the potential to span the 2-20 THz region of the spectrum. In spite of the promise there are a number of technical and implementation issues to be addressed. A method to lock and control the laser needs to be developed. This will ultimately have to address the beam quality, noise and tuning range. It is likely that the current distributed feed back implementation of the existing Quantum Cascade lasers is not ideal for far infrared applications and other implementations may be better. It is likely that the lock scheme will require some components developed from the harmonic generator world. The thermal dissipation of the lasers needs to be reduces and the temperature of operation increased. Lastly care will need to be taken to expand the tuning range to a wider band to minimize the number of lasers necessary for covering wide windows.

The area of photomixing would be very promising if a material could be identified that solves the power handling and conversion problem. If so a single photomixer source could cover or drive all the mixers on a mission like SAFIR.

Back Ends

The spectrometers required for SAFIR will have significantly more channels that those on Herschel. As a result the power per channel will need to be reduced. It would also be highly desirable to be able to re-configure the channel spacing. Since the spectrometer is dominated by commercial digital electronics it is critical to support efforts to "space qualify" modern digital processes. Additionally development and evaluation of dedicated circuits like samplers using state of the art process in industry need to be supported. The evaluations must include radiation tests to asses the suitability of various technologies for space applications. Currently technology exists for a 10 GHz sampler even though the state of the art on Herschel is 550 MHz. The Chirp transformer spectrometers should be developed in the same way. The acousto-optical spectrometer will remain a viable backup to the digital technology should the technology prove un-qualifiable.

System Considerations

The heterodyne world is one of coherent interference problems from standing waves and the requirement for temperature stability. If the temperature is stable the standing wave doesn't change and can be effectively removed from the spectra. Additionally a stable temperature minimizes the gain changes in the IF system and the spectrometer allowing for more accurate calibration of the data. Extreme care must be taken in the design of all apertures so nothing is reflected back into the beam. This must be done at the -80dB level even if the system is relatively stable.

Other system issues are thermal loading and collection of the IF signal. Ideally the first stage of IF amplification would be integrated into the mixer before driving the cable. This results in additional thermal dissipation at the mixer and a requirement to match mixer and first stage amplifier together.

Lastly there is a need for system level prototype demonstrations employing an end to end receiver in the configuration proposed to identify and solve EMC and standing wave problems that always plague heterodyne systems. This is especially true when there is new technology, which never works entirely as advertised.